INTERNATIONAL APPLICATION AS ORIGINALLY FILED

DESCRIPTION

METHOD OF DRIVING ULTRASONIC TRANSDUCER

Technical Field

The present invention relates to a method of driving an ultrasonic transducer for use in measuring sound speed in a liquid or the like by transmitting and receiving an ultrasonic wave.

Background Art

In general, an ultrasonic transducer has a piezoelectric resonator including a pair of electrodes formed by sandwiching a piezoelectric body, and is provided with a backing layer on the back surface of one of the electrodes of this piezoelectric resonator (for example, refer to Patent Document 1). When a drive signal is applied across the pair of electrodes, the piezoelectric resonator is excited to transmit an ultrasonic wave. On the other hand, when an ultrasonic wave is received, the piezoelectric resonator converts the vibration into an electrical signal, and outputs it. Also, the backing layer is provided in order to absorb and attenuate an ultrasonic wave emitted from the piezoelectric resonator to the back surface at excitation time.

When sound speeds in various liquids are measured using such an ultrasonic transducer, a pair of ultrasonic transducers are disposed opposite at a predetermined distance, and an ultrasonic wave is transmitted from one of the ultrasonic transducers. The other of the ultrasonic transducers receives the ultrasonic wave

that has passed through a liquid. A measurement circuit measures the time required for transmission and receiving, and the sound speed in the liquid is calculated on the basis of the measured time and the opposed distance between both of the ultrasonic transducers.

In this case, when the difference of the acoustic characteristic impedance (acoustic characteristic impedance) of the piezoelectric resonator and that of the backing layer disposed on the back face thereof is large, the reflection of a sound wave occurs on the boundary face of both layers to cause resonance in the piezoelectric body, and thus a phenomenon, in which vibration continues without converging in a short time, namely so-called ringing, occurs due to the resonance. When this ringing arises, a ringing component is included in the signal of the received wave to increase measurement errors, causing problems, such as lowering the time resolution. Accordingly, in a known technique, a proposal has been made of an ultrasonic transducer in which a setting is determined such that the acoustic characteristic impedance of the backing layer has substantially the same value as the acoustic characteristic impedance of the piezoelectric body constituting the piezoelectric resonator, and both of them are bonded integrally (for example, refer to Patent Document 2).

Incidentally, when applying a drive pulse to an ultrasonic transducer, the shape of the drive pulse becomes an issue. When a piezoelectric body is used in an ultrasonic transducer, the

applied voltage pulse (= drive pulse) and the displacement have substantially the same waveform, and the sound pressure and the particle speed of the generated ultrasonic wave pulse comes to have substantially the same waveform as the time differentiation of the applied voltage pulse. That is to say, when the drive pulse is a rectangular wave, the differentiation of a rise of a pulse becomes one mountain rising and falling, whereas a fall of a pulse becomes a valley falling and rising on the contrary. In short, when a drive pulse of a rectangular shape is applied, a sound wave is generated by the differentiation value of the pulse. Thus, for example an ultrasonic waveform having two consecutive changes, a mountain and a valley, is generated as a waveform of Td = 350 nsec in Fig. 5. In this regard, when the element is driven using a transistor, etc., the drive current is limited, and thus the voltage across the terminals of the element becomes a triangular wave rather than a rectangular wave if the electrostatic capacity thereof is large. This causes the lowering of the sound pressure of the generated ultrasonic pulse, and thus it is desirable to make the drive current as large as possible and to make the electrostatic capacity of the element as small as possible in order to make the voltage across the terminals as near as a rectangular wave at implementation time. When the pulse width is wide, the mountain and a valley are separated in time.

On the other hand, when the sound speed in various liquids as described above are measured, the measurements are made of the

time required from applying a drive pulse shown in Fig. 23(a) to an ultrasonic transducer to the receiving of the wave. At that time, from example, as shown in Figs. 23(b) and 23(c), if the receiving side measures T1, which is the time period for the wave to reach the vicinity of the peak of the mountain waveform or the valley peak, the measurement is liable to be affected by the gain of an amplifier, noises, etc., and thus the measurement precision is apt to be deteriorated. Accordingly, up to now, as shown in Figs. 23(d) and 23(e), the detection has been carried out on T2, which is the time of crossing the point of a zero amplitude during a fall from a mountain toward the next valley, namely up to a zero-cross point.

Patent Document 1: Japanese Unexamined Patent Application Publication No. 15-259490

Patent Document 2: Japanese Unexamined Patent Application Publication No. 2003-37896

Disclosure of Invention

Problems to be Solved by the Invention

In order to detect the zero-cross point of a received signal with high precision as described above, it is desirable that the gradient of the waveform at the zero-cross point is as sharp as possible. However, in a known technique, the waveform of the drive pulse to be applied to an ultrasonic transducer, particularly the pulse width, has not been fully examined. Thus, measurement errors increase. For example, the detection position becomes unclear when the zero-cross point is detected.

Accordingly, problems, such as the decrease of time resolution, etc., have occurred.

Also, when a setting is determined such that the acoustic characteristic impedance of the backing layer has substantially the same value as the acoustic characteristic impedance of the piezoelectric body constituting the piezoelectric resonator as disclosed in Patent Document 2, it becomes possible to suppress the reflection on the boundary face of both of the layers to a certain extent.

However, even in that case, the reflection of an ultrasonic wave occurs on the end face of the open side, which is the opposite side of the backing layer to the boundary face with the piezoelectric resonator, and thus this reflection component is transmitted to the receiving side to cause measurement errors. Accordingly, it is necessary to prevent the influence of the reflection on the end face of the open side of the backing layer.

The present invention has been made in view of the above-described problems. It is an object of the present invention to provide a method of driving an ultrasonic transducer capable of increasing the detection precision of the zero-cross point and improving the measurement precision of the ultrasonic wave better than before without being influenced by the reflection on the end face of the open side of the backing layer.

Means for Solving the Problems

In order to achieve the above-described object, according to the invention described in Claim 1, there is provided a method of

driving an ultrasonic transducer having a piezoelectric resonator formed by a pair of electrodes sandwiching a piezoelectric body and provided with a backing layer contacting with one of the electrodes of the piezoelectric resonator and having the same acoustic characteristic impedance as the piezoelectric body, the method including the step of driving so as to satisfy a condition:

$2Th \leq Td \leq 6Th$

where Th is a propagation time of an ultrasonic wave in the piezoelectric body sandwiched by the pair of electrodes, and Td is a pulse width of a drive pulse driving the piezoelectric resonator.

The method of driving an ultrasonic transducer according to the invention described in Claim 2 is, in the method of driving described in Claim 1, a setting is determined so as to satisfy a condition:

$Td < (2L2 + L1)/V$

where L1 is a thickness of the piezoelectric body sandwiched by the pair of electrodes, L2 is a thickness of the backing layer, and V is a sound speed when an ultrasonic wave propagates in the piezoelectric body and the backing layer.

The method of driving an ultrasonic transducer according to the invention described in Claim 3 is, in the method of driving described in Claim 1 or Claim 2, when a pair of the ultrasonic transducers are disposed opposite with sandwiching a substance to be an ultrasonic transmission target, a setting is determined so

as to satisfy a condition:

$$(R^2 + X^2)^{1/2} - X > (VM \times Td)$$

where X is a distance between both of the opposite ultrasonic transducers, 2R is a length of a short side or a diameter of an ultrasonic wave emission surface, VM is a sound speed of an ultrasonic wave propagating in the substance, and λ is a wavelength of the ultrasonic wave propagating in the substance, represented by $\lambda = (VM \times Td)$.

The method of driving an ultrasonic transducer according to the invention described in Claim 4 is, in the method of driving described in any one of claims 1 to 3, when there is a partition wall made of a substance different from a substance of an ultrasonic wave emission surface of the piezoelectric resonator and a substance to be a target of ultrasonic transmission therebetween, a setting is determined so as to satisfy a condition:

$$Td < 2Lw/Vw$$

where Lw is a thickness of the partition wall, and Vw is a sound speed when an ultrasonic wave propagates in the partition wall.

The method of driving an ultrasonic transducer according to the invention described in Claim 5 is, in the method of driving described in Claim 4, a setting is determined such that an acoustic characteristic impedance has a value between an acoustic characteristic impedance of the piezoelectric resonator and an acoustic characteristic impedance of the substance to be a target

of ultrasonic transmission.

Advantages

By the method of driving an ultrasonic transducer according to the invention described in Claim 1, the pulse width of the drive pulse is set to satisfy a certain condition at the transmission side, and thus it is possible to keep the slope of the waveform at the zero-cross point sharp at the receiving side. Thus, it is possible to increase the detection precision of the zero-cross point. Accordingly, the time resolution improves better than before when an ultrasonic wave is received, and thereby it becomes possible to measure sound speed with high precision.

By the method of driving an ultrasonic transducer according to the invention described in Claim 2, the pulse width of the drive pulse or the thickness of the backing layer is set to satisfy a certain condition at the transmission side, and thus the receiving side is not influenced by the reflection on the end face of the open side of the backing layer at an ultrasonic-wave transmission time. Accordingly, it becomes possible to improve the measurement precision of the ultrasonic wave better than before.

By the method of driving an ultrasonic transducer according to the invention described in Claim 3, the distance X between the pair of ultrasonic transducers is set to satisfy a certain condition, and thus the ultrasonic wave is received in a near acoustic field. Accordingly, it is possible to eliminate the

influence of a diffracted wave, and thus it becomes possible to improve the measurement precision of the ultrasonic wave better than before.

By the method of driving an ultrasonic transducer according to the invention described in Claim 4, when there is a partition wall made of a substance different from a substance of an ultrasonic wave emission surface of the piezoelectric resonator and a substance to be a target of ultrasonic transmission therebetween, the pulse width of the drive pulse or the thickness of the partition wall is set to satisfy a certain condition, and thus it is possible for the receiving side to eliminate the influence of the reflection caused on the partition wall. Accordingly, the time resolution improves better than before when an ultrasonic wave is received, and thereby it becomes possible to measure sound speed with high precision.

By the method of driving an ultrasonic transducer according to the invention described in Claim 5, an acoustic characteristic impedance has a value between an acoustic characteristic impedance of the piezoelectric resonator and an acoustic characteristic impedance of the substance to be a target of ultrasonic transmission, and thus the amount of attenuation by the reflection of the ultrasonic wave on the partition wall can be made small. Accordingly, it is possible to efficiently transmit an ultrasonic wave toward the receiving side.

Best Mode for Carrying Out the Invention

According to the present invention, the method of driving an

ultrasonic transducer has a piezoelectric resonator formed by a pair of electrodes sandwiching a piezoelectric body and provided with a backing layer contacting with one of the electrodes of the piezoelectric resonator and having the same acoustic characteristic impedance as the piezoelectric body, the method including the step of driving so as to satisfy a condition:

$$2Th \leq Td \leq 6Th \qquad (1)$$

where Th is a propagation time of an ultrasonic wave in the piezoelectric body sandwiched by the pair of electrodes, and Td is a pulse width of a drive pulse driving the piezoelectric resonator.

When measuring sound speeds in various liquids, it is preferable to have the gradient of the waveform at the zero-cross point as sharp as possible in order to detect the zero-cross point of the signal of the received wave with high precision. That is to say, when the pulse width Td of the drive pulse is too wide, the gradient of the waveform at the zero-cross point becomes moderate, and thus the zero-cross point becomes unclear. Also, when the pulse width Td is extremely narrow, the signal level becomes low, and thus the S/N ratio is deteriorated. In addition, the degree of change from a mountain to a valley becomes small, and thus the gradient of the waveform at the zero-cross point becomes moderate, resulting in an unclear zero-cross point. In contrast, when the pulse width Td of the drive pulse is set so as to satisfy the above-described condition (1), it is possible to make the gradient of the waveform at the zero-cross

point sharp. Accordingly, it is possible to increase the detection precision of the zero-cross point, and thus it is possible to increase the measurement precision of the ultrasonic wave better than before.

Also, in the method of driving an ultrasonic transducer according to the present invention, when employing the above-described driving method, a setting is determined so as to satisfy a condition:

$$Td < (2L2 + L1)/V \qquad (2)$$

where L1 is a thickness of the piezoelectric body sandwiched by the pair of electrodes, L2 is a thickness of the backing layer, and V is a sound speed when an ultrasonic wave propagates in the piezoelectric body and the backing layer.

If the thickness L2 of the backing layer is set to satisfy the above-described condition (2) in advance, it is possible to separate in time the ultrasonic wave directly generated from the piezoelectric resonator and the ultrasonic wave reflected on the end face of the open side of the backing layer. Accordingly, it is possible to eliminate the influence of the ultrasonic wave reflected on the end face of the open side of the backing layer, and thus it is possible to improve the measurement precision of the ultrasonic wave better than before. In this regard, the pulse width Td of the drive pulse may be set to satisfy the above-described condition (2) in place of setting the thickness L2 of the backing layer. In this regard, when an ultrasonic transducer having the same structure as the transmitter is used

as a receiver, the receiver should be set to satisfy the condition (2).

Furthermore, in the method of driving an ultrasonic transducer according to the present invention, when a pair of ultrasonic transducers are disposed opposite with sandwiching a substance to be an ultrasonic transmission target, a setting is determined so as to satisfy a condition:

$$(R^2 + X^2)^{1/2} - X > (VM \times Td) \qquad (3)$$

where X is a distance between both of the opposite ultrasonic transducers, 2R is a length of a short side or a diameter of an ultrasonic wave emission surface, VM is a sound speed of an ultrasonic wave propagating in the substance, and λ is a wavelength of the ultrasonic wave propagating in the substance, represented by $\lambda = (VM \times Td)$.

That is to say, the ultrasonic wave to be transmitted includes direct waves simultaneously emitted from allover the transmission face and the diffracted wave having reverse polarity emitted from the edge portion of the transmission face. However, when the distance X between the pair of the ultrasonic transducers is set to satisfy the above-described condition (3), the ultrasonic wave is received in a near acoustic field, and thus it is possible to separate and eliminate the influence of the diffracted wave in time. Accordingly, it becomes possible to improve the measurement precision of the ultrasonic wave better than before.

Moreover, in the method of driving an ultrasonic transducer

according to the present invention, when there is a partition wall made of a substance different from a substance of the ultrasonic wave emission surface of the piezoelectric resonator and a substance to be a target of ultrasonic transmission therebetween, a setting is determined so as to satisfy a condition:

$$Td < 2Lw/Vw \qquad (4)$$

where Lw is a thickness of the partition wall, and Vw is a sound speed when an ultrasonic wave propagates in the partition wall.

If the thickness Lw of the partition wall is set to satisfy the above-described condition (4), it is possible to eliminate the influence of the reflection caused on the partition wall at the receiving side. That is to say, it is possible to separate in time the ultrasonic wave directly generated from the piezoelectric resonator and the ultrasonic wave reflected on the end face of the partition wall. Accordingly, the time resolution improves better than before when an ultrasonic wave is received, and thereby it becomes possible to measure a sound speed with high precision. In this regard, the pulse width Td of the drive pulse may be set to satisfy the above-described condition (4) in place of setting the thickness Lw of the partition wall.

Also, in the method of driving an ultrasonic transducer according to the present invention, a setting is determined such that an acoustic characteristic impedance of the partition wall has a value between an acoustic characteristic impedance of the

piezoelectric resonator and an acoustic characteristic impedance of the substance to be a target of ultrasonic transmission. Thus, the amount of attenuation by the reflection of the ultrasonic wave on the partition wall can be made small. Accordingly, it is possible to efficiently transmit an ultrasonic wave toward the receiving side. As a matter of course, when an ultrasonic transducer having the same structure as the transmitter is used as a receiver, it is preferable to set the thickness Lw of the partition wall and the acoustic characteristic impedance as described above.

In the following, a description will be given of specific embodiments which become a basis of employing the above-described method of driving an ultrasonic transducer.

First embodiment

Fig. 1 illustrates the configuration of an ultrasonic transducer in this first embodiment. Fig. 1(a) is a sectional view, and Fig. 1(b) is a sectional view taken along line Z-Z of Fig. 1(a). Fig. 2 is a planar sectional view illustrating the specific size and shape of the electrode of this ultrasonic transducer.

The ultrasonic transducer 1 of this first embodiment includes a piezoelectric body 3 made of a ceramic material such as a lead zirconate titanate (PZT), etc., and a pair of electrodes 4 and 5 are formed in the piezoelectric body 3 with a predetermined distance. The portion of the piezoelectric body 3 sandwiched by the above-described pair of electrodes 4 and 5 is

subjected to polarization processing to constitute a piezoelectric active portion 31. Thus, a piezoelectric resonator 2 is constituted by this piezoelectric active portion 31 and the pair of electrodes 4 and 5.

Furthermore, the portion of the piezoelectric body located outside of one of electrodes 5 of this piezoelectric resonator 2 is formed as a backing layer 32. Also, the outside of the other of electrodes 4 is provided with a thin outer layer 33. Accordingly, the piezoelectric active portion 31, the backing layer 32, and the outer layer 33, which constitute the piezoelectric resonator 2, are integrated together to have the same acoustic characteristic impedance. In this regard, the backing layer 32 and the outer layer 33 are non-polarized and in a non-active state, but may have been subjected to polarization processing. Also, external connection electrodes 7 and 8, which are individually connected to the lead-out portions 4a and 5a of the electrodes 4 and 5, respectively, are formed on the end face of the side perpendicular to the electrode-formed face of the piezoelectric resonator 2.

In this first embodiment, the ultrasonic transducer 1 having the above-described configuration is produced as follows. First, water and binder is added to piezoelectric ceramic powder whose main component is a lead zirconate titanate (PZT) to form a sheet. The thickness of this ceramic sheet per one layer is about 65 μm before sintering and about 40 μm after sintering. Silver-palladium paste is printed on the portion corresponding to the

electrodes 4 and 5 by a screen printing method. The amount of palladium is selected in a range of 0 to 80% depending on a burning condition, etc. Here, the amount was determined to be 30%.

Using the above-described sheets, four layers of the ceramic sheets were laminated for forming the piezoelectric active portion 31, 37 layers were laminated for forming the backing layer 32, and one layer was laminated for forming the outer layer. The sheets were integrally burned at a temperature up to a maximum of about 100° C. The entire dimensions of the ultrasonic transducer 1 were 6 × 9 × 1.7 mm after burning. At that time, the thickness of the piezoelectric active portion 31 was about 160 μm, the thickness of the backing layer 32 was about 1.5 mm, and the thickness of the outer layer 33 was about 40 μm. Also, as shown in Fig. 2, the thickness of each of the electrodes 4 and 5 is 1 to 2 μm, the size of the portion of each of the electrodes 4 and 5, which is opposed to the piezoelectric active portion 31, is a 5.5-mm square, and the width of the lead-out portions 4a and 5a is 0.5 mm. The lead-out portions 4a and 5a are shifted with each other in order not to have piezoelectric activity.

Next, in order to electrically connect each of the electrodes 4 and 5 and the outside, external connection electrodes 6 and 7 were formed on the exposed portion to the side face of the lead-out portions 4a and 5a of the electrodes 4 and 5. The external connection electrodes 6 and 7 were formed by applying electrode paste made of silver powder and glass powder

and burning at a temperature of about 800°C. In this regard, a metal film can be formed by a method using a vacuum technique such as deposition and sputtering. Next, polarization processing was performed by applying a direct current of 480 V across both of the external connection electrodes 6 and 7.

The ultrasonic transducer 1 created in this manner was disposed in a water tank 10 as shown in Fig. 3. The ultrasonic wave emitted from the ultrasonic transducer 1 was received by a PVDF hydrophone 11, and the received waveform was observed by a digital oscilloscope 13 through a pre-amplifier 12. The driving of the ultrasonic transducer 1 was carried out by generating a single-shot pulse having various pulse widths by a pulse generator 14 and applying this pulse to the ultrasonic transducer 1 through a driver 15. That is to say, as shown in Fig. 4, a single-shot pulse is directly applied to one of the electrodes 4 through an amplifier 15a using an inverter of the driver 15. Also, the pulse amplified by the amplifier 15a is level-inverted through an inverter 15b, and then is applied to the other of the electrodes 5. In this regard, the basic operation is the same in the case of using only one inverter rather than using two inverters. That is to say, in the present invention, the control of the pulse width is important regardless of the driving method.

Fig. 5 shows the waveforms observed at the propagation distance X = 5 mm when ultrasonic waves were transmitted by applying a single-shot pulse having various pulse widths Td across both electrodes of the ultrasonic transducer 1. Also, Fig.

6 is measured results of individual sound pressures of a mountain peak and a valley peak of the received waveform when the pulse width Td of the drive pulse is changed.

As is understood from these figures, when the pulse width Td is in a small range less than 80 nsec, each amplitude of a mountain and a valley is also small, the degree of change is mild, the waveforms of a mountain and a valley are asymmetric, and thus the zero-cross point is not clear. Also, when the pulse width Td is larger than 250 nsec, a mountain and a valley of the waveform of an ultrasonic wave is separated, the slope of the waveform at the zero-cross point becomes mild, and thus the detection point at the time of detecting the zero-cross point becomes unclear.

In contrast, when the pulse width Td is between 80 nsec and 250 nsec, the symmetry of a mountain and a valley of a ultrasonic waveform is good, and the gradient of the waveform at the zero-cross point changing from a mountain to a valley is relatively sharp. Thus, it is possible to detect the zero-cross point with high precision.

In the case of the first embodiment, the thickness of the piezoelectric active portion 31 constituting the piezoelectric resonator 2 is about 160 μm, the sound speed at that time is about 4000 m/s, and thus the propagation time Th of the piezoelectric active portion 31 is about 40 nsec. The detection precision of the zero-cross point is high when the pulse width Td is between 80 nsec and 250 nsec as described above. Thus, when specifying the pulse width Td by the propagation time Th, it is

understood that the zero-cross point can be detected clearly if the pulse width Td of the drive pulse is set in a range of two to six times the propagation time Th of an ultrasonic wave passing the piezoelectric active portion 32. Accordingly, if the driving is carried out by setting the pulse width Td of the drive pulse to satisfy $2 \leq (Td/Th) \leq 6$, namely the above-described condition (1), it is possible to clearly detect the zero-cross point.

Moreover, the optimum range for clearly detecting the zero-cross point is $2 \leq (Td/Th) \leq 3$. The reason for this will be described with reference to Figs. 24 to 26.

First, an ideal case is considered. When a drive pulse (a pulse width Td) shown in Fig. 24(a) is applied to the ultrasonic transducer 1, the displacement waveform at that time becomes as shown in the same figure (b). Also, at this time, the waveform of the sound pressure generated from the ultrasonic transducer 1 becomes as shown in the same figure (c). In this case, assuming that the displacement waveform needs the time Th at a rise and a fall of the drive pulse, individually, the width of the mountain and the width of the valley of the sound waveform become the same Th. In order to have good symmetry in the mountain and the valley of the ultrasonic waveform and a sharp slope of the waveform at the zero-cross point, it is necessary that the time period between the mountain and the valley of the ultrasonic waveform $Tg \approx 0$. Accordingly, when $Td = Th$ as shown in Fig. 25(a), the optimum ultrasonic waveform is obtained as shown in the same figure (b).

However, the actual drive pulse has a waveform just like a waveform of discharging an electrical charge charged in a capacitor through a resistor as shown in Fig. 26(a), and thus, the displacement waveform of the ultrasonic transducer 1 needs Tr + Th as the time from the start of the application of the drive pulse to the piezoelectric body 3 to the end as shown in the same figure (b) in consideration of the rise time Tr of the signal. Thus, the waveform of the sound wave generated from the ultrasonic transducer 1 becomes the one as shown in the same figure (c). Also, in this case, in order to have a sharp slope of the waveform at the zero-cross point, it is necessary that the time period between the mountain and the valley of the ultrasonic waveform Tg ≈ 0. Accordingly, the optimum ultrasonic waveform is virtually obtained when

$$Td = Tr + Th. \qquad (I)$$

However, the rise time Tr of the signal shown in Fig. 26 depends on the actual use condition, the circuit configuration, etc. The condition for obtaining the maximum voltage by the minimum electric current source is at the time of Th = Tr. When applying this condition to the above-described expression (I), the result becomes Td = 2Th, namely Td/Th = 2. In reality, Tr becomes somewhat larger than Th, and thus Td/Th = 2 shows the lower limit of the optimum range for detecting the zero-cross point clearly.

On the other hand, the upper limit of the optimum range for clearly detecting the zero-cross point depends on the value of Tr.

The result of the experiment shown in Fig. 5 indicates that Td/Th = 6 (namely, Td = 250 nsec) is the upper limit. However, as is read out from Fig. 5, when Td/Th = 6, the mountain and the valley of the ultrasonic waveform are somewhat separated, and thus the zero-cross point becomes rather unclear. Accordingly, the result of the experiment shown in Fig. 5 indicates that Td/Th = 3 (namely, Td = 120 nsec) is more desirable.

Second embodiment

Fig. 7 shows the relationship between the ultrasonic wave directly emitted from the emission face of the piezoelectric resonator 2 and the ultrasonic wave reflected from the open-end surface 32a of the backing layer 32 and passing through the piezoelectric resonator 2 again to be emitted in the ultrasonic transducer 1 having the configuration shown in Fig. 1. Also, Fig. 8 shows the comparison between the drive pulse to be added to the ultrasonic transducer 1 and the waveform of the ultrasonic wave at the receiving time.

In the waveform at the time of receiving an ultrasonic wave, the time from the point of a rise of a mountain to the zero-cross point is substantially equal to the pulse width Td of the drive pulse. Accordingly, if the time Te, which is required for the ultrasonic wave generated by the piezoelectric resonator 2 to return to the emission surface of the piezoelectric resonator 2 again by being reflected from the open-end surface 32a of the backing layer 32, is larger than the pulse width Td of the drive pulse (Te > Td), it is possible to separate in time the

ultrasonic wave directly emitted from the emission face of the piezoelectric resonator 2 and the ultrasonic wave reflected from the open-end surface 32a of the backing layer 32 at the receiving side.

Here, assuming that L1 is a thickness of piezoelectric active layer 31, L2 is a thickness of the backing layer 32, and V is a sound speed when an ultrasonic wave propagates in the piezoelectric active layer 31 and the backing layer 32, $Te = (2L2 + L1)/V$. Accordingly, if the thickness L2 of the backing layer 32 is set to satisfy $(2L2 + L1)/V > Td$, that is to say, the above-described condition (2) in advance, it is possible to eliminate the influence of the ultrasonic wave reflected on the end face of the open side of the backing layer 32. In this regard, the pulse width Td of the drive pulse may be set to satisfy the above-described condition (2) in place of setting the thickness L2 of the backing layer.

Third embodiment

Fig. 9 and Fig. 10 are explanatory diagrams when a pair of ultrasonic transducers, which are driven with the configuration and the condition described in the first and the second embodiments, are disposed opposite at a predetermined distance to constitute an ultrasonic wave transmitter/receiver.

The ultrasonic wave transmitter/receiver 20 shown in Fig. 9 is produced by forming two pairs of opposed electrodes 4a and 5a, and 4b and 5b in the piezoelectric body 3 and cutting away the central portion located between each pair of the upper and the

lower electrodes 4a and 5a, and 4b and 5b into a U-shape by cutting process, etc. Thus, the ultrasonic wave transmitter/receiver 20 has a configuration in which a pair of ultrasonic transducers 1a and 1b having the same structure as the one shown in Fig. 1 are concatenated through a supporting member 34.

Accordingly, a pair of electrodes 4a and 5a located in the upper part and the piezoelectric body sandwiched by these electrodes 4a and 5a, that is to say, the piezoelectric active portion 31a constitute a piezoelectric resonator 2a, and a backing layer 32a is formed on the back side of one of the electrodes 5a to constitute one of ultrasonic transducers 2a. Similarly, a pair of electrodes 4b and 5b located in the lower part and the piezoelectric body sandwiched by these electrodes 4b and 5b, that is to say, the piezoelectric active portion 31b constitute a piezoelectric resonator 2b, and a backing layer 32b is formed on the back side of one of the electrodes 5b to constitute one of ultrasonic transducers 2b. The ultrasonic wave transmitter/receiver 20 having this configuration has advantages in that it needs only a few production man-hour, and it is easy to align both of the ultrasonic transducers 1a and 1b.

The ultrasonic wave transmitter/receiver 21 shown in Fig. 10 is produced by bonding a pair of ultrasonic transducers 1a and 1b having substantially the same structure as the one shown in Fig. 1, respectively, using a spacer 22 and adhesive in a U-shape.

Here, in the ultrasonic wave transmitters/receivers 20 and

21 shown in Fig. 9 or Fig. 10, the opposed distance X between the ultrasonic wave emission surfaces of a pair of ultrasonic transducers 1a and 1b is desirably set as follows.

Now, as shown in Fig. 11, assuming that an ultrasonic wave is transmitted from one of (for example, a lower side) ultrasonic transducers 1b toward the other of (here, an upper side) ultrasonic transducers 1a, the ultrasonic waves to be transmitted include a direct wave emitted from allover the transmission face of the lower-side ultrasonic transducers 1b and a diffracted wave having reverse polarity emitted from the edge portion of the transmission face.

When the direct wave and the diffracted wave reach the ultrasonic transducer 1a of the receiving side without overlapping, the zero-cross point from a mountain to a valley of the received waveform is clear as shown in Fig. 12(a). However, when the direct wave and the diffracted wave reach the ultrasonic transducer 1a of the receiving side with overlapping, as shown in Fig. 12(b), there are two zero-cross points, from a mountain to a valley and from a valley to a mountain, of the received waveform before and after in a row, and thus it is difficult to detect the zero-cross point with high precision. Accordingly, this results in deterioration of the time resolution at the time of receiving an ultrasonic wave.

Here, assuming that X is an opposed distance on an acoustic axis 23 connecting a center of the ultrasonic wave face of the lower-side ultrasonic transducer 1b and a center of the

ultrasonic wave face of the upper-side ultrasonic transducer 1a, 2R is a length (a diameter when the electrode 4b is a circle) of a short side of the electrode 4b of the ultrasonic-wave emission surface, VM is a sound speed of a ultrasonic wave propagating in the substance sandwiched by the upper and lower ultrasonic transducers 1a and 1b, a wavelength λ of the ultrasonic wave propagating in the substance is represented by $\lambda = VM \times Td$. A distance from the edge of the ultrasonic wave surface of one of the ultrasonic transducers 1b to the acoustic axis 23 of the ultrasonic wave surface of the other of the ultrasonic transducers 1a is represented by $(R^2 + X^2)^{1/2}$.

Now, when an ultrasonic wave emitted from the center of the ultrasonic wave face of the lower-side ultrasonic transducer 1b travels the distance X and reaches the upper-side ultrasonic transducer 1a, the diffracted wave emitted from the edge also travels the same distance X. In order to separate the direct wave and the diffracted wave in time, it is necessary that the difference of distance $\Delta = (R^2 + X^2)^{1/2} - X$ between the direct wave and the diffracted wave at the time of the direct wave reaching the receiving side of the ultrasonic transducer 1a is more than the $VM \times Td$ apart, which is the product of the sound speed VM of a ultrasonic wave propagating in the substance and the pulse width Td of the pulse.

Accordingly, if the opposed distance X is set to satisfy $\Delta > \lambda$, that is to say, the above-described condition (3), it is possible to separate the direct wave and the diffracted wave in

time, and to detect the zero-cross point with high precision. In this regard, in this case, it is desirable for the above-described difference of the distance Δ to have a value as larger as possible than the wavelength λ. That is to say, it is desirable to be in a near acoustic field. If Δ is too small (that is to say, the opposed distance X is large and in a far acoustic field), the direct wave and the diffracted wave cannot be separated. In this regard, if the ultrasonic transducer of the receiving side is large, the waves are received even when the direct wave and the diffracted wave cannot be separated. However, the direct wave enters with the same phase on allover the receiving wave surface, whereas the diffracted wave enters with different phases continuously. Thus, the influence of the diffracted wave as a result becomes very small.

Fig. 13 is a graph plotting $\lambda = \Delta\{\sqrt{(R^2 + X^2)}\} - X$ using the length of the short side or the diameter 2R of the ultrasonic wave transmission surface as a parameter. If a point is below this graph, it is in a near acoustic field, and if a point is above, it is in a far acoustic field.

Fourth embodiment

In this fourth embodiment, an examination has been made on various characteristics of the ultrasonic wave transmitter/receiver having the configuration of the third embodiment shown in Fig. 9 and Fig. 10.

Fig. 14 shows the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water

temperature, using the ultrasonic transmitter/receiver 20 having the configuration shown in Fig. 9. In this regard, the value at 70°C is indicated as 0 nsec here. Also, the calculated value in the same figure was obtained from the distance X ≈ 1.4 mm between the ultrasonic transducers 1a and 1b and the document value. As is understood from Fig. 14, the difference between the measured result and the calculated value is small, and that repeated measurement precision is good.

Fig. 15 shows the results obtained by measuring ultrasonic wave propagation time in water, which changes with the water temperature, using the ultrasonic transmitter/receiver 21 having the configuration shown in Fig. 10. In this regard, the same figure (a) is the case of integrating a pair of ultrasonic transducers 1a and 1b, and the spacer 22 by bonding with epoxy resin. Also, the same figure (b) is the case of integrating a pair of ultrasonic transducers 1a and 1b, and the spacer 22 by bonding with glass.

The comparison of both of them shows that the one in which the spacer 22 is bonded with glass has a smaller error from the document value, and a better repetition precision. On the other hand, the one in which the spacer 22 is bonded with epoxy resin has larger variations and the difference from the document values. Thus, it is inappropriate for the case of demanding high time resolution. The reason for this is inferred that the distance between the pair of ultrasonic transducers 1a and 1b has changed by the deformation of the resin due to the change of the water

temperature.

Fifth embodiment

In this fifth embodiment, in the case of using the ultrasonic transmitters/receivers 20 and 21 having the configuration of the third embodiment shown in Fig. 9 and Fig. 10, for example, as shown in Fig. 16, there is sometimes a partition wall 25 such as a pipe between the pair of ultrasonic transducers 1a and 1b, and a substance 24 such as a liquid, etc., to be the target of measurement of the sound speed. The influence to that partition wall 25 is examined. Here, a polycarbonate having a thickness Lw = 0.2 mm was used for the partition wall 25, and water was used for the substance 24 through which an ultrasonic wave propagates. The sound speed in the polycarbonate to be the partition wall 25 was about 2330 m/s.

Fig. 17(a) is a result obtained by measuring the propagation of an ultrasonic wave in a state of dipping in water the ultrasonic transmitter/receiver 20 having the configuration shown in Fig. 9 without change. Fig. 17(b) is a result obtained by measuring the propagation of an ultrasonic wave in a state of disposing a partition wall 25 between the ultrasonic transmitter/receiver 20 and water 24. In Figs. 17(a) and (b), a curve in the upper row is the waveform of a drive pulse of an amplitude of 4.5 V and a time width of 100 nsec. A curve in the middle row is a waveform produced by amplifying 20 times the signal propagated to the ultrasonic transducer 1a of the receiving side. A curve in the lower row is produced by

enlarging the portion marked by a reference numeral P of the curve in the middle row. In this regard, adhesive such as epoxy resin, silicon rubber, etc., are thinly applied to the ultrasonic transmitter/receiver 20 and the partition wall 25.

As is understood from Fig. 17, the transmission and receiving of an ultrasonic wave are possible even if there is a partition wall 25, and significant variations cannot be seen in the amplitude of the received waveform. However, when there is a partition wall 25 between the ultrasonic transmitter/receiver 20 and water 24, as shown in Fig. 18, ultrasonic waves are received both from the direct wave emitted from the transmission surface of the ultrasonic transducer 1b of the transmission side and the ultrasonic wave reflected on the end face of the partition wall 25. Fig. 17(b) shows a state of having received both of such direct wave and the ultrasonic wave reflected on the end face of the partition wall. Accordingly, when the direct wave and the reflected wave are received in an overlapping state, it becomes difficult to detect the zero-cross point with high precision.

In order to separate the direct wave emitted from the transmission surface of the ultrasonic transducer 1b of the transmission side and the ultrasonic wave reflected on the end face of the partition wall 25, it is necessary that the time Tw required for going to and coming back in the partition wall 25 is longer than the pulse width Td of the drive pulse (Tw > Td). Accordingly, in Fig. 18, assuming that Lw is the thickness of the partition wall 25 and Vw is the sound speed propagated in the

partition wall 25, $Tw = 2Lw/Vw$. Thus, if the thickness Lw of the partition wall 25 is set to satisfy $2Lw/Vw > Td$, namely the above-described condition (4), it is possible to separate the direct wave and the reflected wave in time, and to detect the zero-cross point with high precision.

From such a viewpoint, the measurements were made on the propagation of the ultrasonic wave in the case of the partition wall 25 made of a polycarbonate having thicknesses of 0.2 mm and 0.5 mm, respectively. The result is shown in Fig. 19. Fig. 19(a) is the case of the partition wall 25 having the thickness $Lw = 0.2$ mm. Fig. 19(b) is the case of the partition wall 25 having the thickness $Lw = 0.5$ mm. In each of the figures, a curve in the upper row is the waveform of a drive pulse of an amplitude of 4.5 V and a time width of 100 nsec. A curve in the middle row is a waveform produced by amplifying 20 times the signal propagated to the ultrasonic transducer 1a of the receiving side. A curve in the lower row is produced by enlarging the portion marked by a reference numeral P of the curve in the middle row. As shown by the comparison of Figs. 19(a) and 19(b), if the thickness Lw of the partition wall 25 is set to satisfy the condition of the above-described (4), it is understood that the influence of the reflected wave on the direct wave is eliminated.

Sixth embodiment

In this sixth embodiment, as in the above-described fifth embodiment, the influence of the material of the partition wall

25 has been examined when there is a partition wall 25 such as a pipe, etc., between the pair of ultrasonic transducers 1a and 1b, and a substance 24 to be the target of measuring the sound speed.

Here, the measurements were made on the propagation state of the ultrasonic waves using a polycarbonate and a liquid crystal polymer as a material of the partition wall 25, individually, the partition wall 25 has a thickness Lw = 0.5 mm in both of the cases, and water is used as the substance 24 through which the ultrasonic wave propagates. The result is shown in Fig. 20. Fig. 20(a) is the case of the partition wall 25 made of a polycarbonate, and Fig. 20(b) is the case of the partition wall 25 made of a liquid crystal polymer. In each of the figures, a curve in the upper row is the waveform of a drive pulse of an amplitude of 4.5 V and a time width of 100 nsec. A curve in the middle row is a waveform produced by amplifying 20 times the signal propagated to the ultrasonic transducer 1a of the receiving side. A curve in the lower row is produced by enlarging the portion marked by a reference numeral P of the curve in the middle row. As is understood from this result, it is possible to transmit and receive ultrasonic waves using not only a polycarbonate but also a liquid crystal polymer as the material of the partition wall 25, and the S/N ratio thereof is good.

As shown in Fig. 21, both of the materials, a polycarbonate and a liquid crystal polymer, to be the partition wall 25 has an acoustic characteristic impedance value between the acoustic

characteristic impedance of the piezoelectric ceramic constituting the ultrasonic transducers 1a and 1b and the acoustic characteristic impedance of the substance 24 (here, water) to be the target of the ultrasonic wave transmission. Accordingly, it is possible to reduce the amount of attenuation by the reflection of the ultrasonic wave on the partition wall 25, and thus it is possible to transmit an ultrasonic wave to the receiving side efficiently.

In this regard, when the ultrasonic transmitters/receivers 20 and 21 shown in Fig. 9 or Fig. 10 are actually used, for example a flow tube 27 having a shape as shown in Fig. 22 can be used. Fig. 22(a) is a partially cutaway front view showing the state in which the ultrasonic transmitter/receiver is attached, Fig. 22(b) is a side view thereof, and Fig. 22(c) is a sectional view taken along line Y-Y of Fig. 22(a).

This flow tube 27 is made of a polycarbonate, has a rectangular flow path 27a formed inside along the longitudinal direction, and has concave portions 27b and 27c formed on the right side and the left side, respectively. By attaching each of the ultrasonic transducers 1a and 1b of the ultrasonic transmitters/receivers 20 and 21 shown in Fig. 9 or Fig. 10 as opposed in each of the concave portions 27b and 27c, it is possible to measure the sound speed of the liquid flowing through the flow path 27a.

By using such a flow tube 27, when measuring the flow speed of a corrosive liquid flowing through the flow path 27a, it is

possible to measure the flow speed without deteriorating the reliability of the ultrasonic transmitters/receivers 20 and 21. Also, for example by attaching an integrated circuit having a function of measuring a temperature additionally, it is possible to constitute an integrated module of the flow tube 27, the ultrasonic transmitters/receivers 20 and 21, and the integrated circuit. Also, by having such a structure, it is possible to omit the spacer member 22 in Fig. 10, and thus it is possible to have a simpler configuration.

In this regard, in the above-described first to sixth embodiments, piezoelectric ceramic is used for the piezoelectric body 3 of the ultrasonic transducers 1, 1a and 1b. However, the present invention is not limited to this. For example, it is possible to apply a high molecular PVDF piezoelectric body, or the like.

Industrial Applicability

A method of driving an ultrasonic transducer of the present invention can be used for an ultrasonic transducer in the case of measuring a sound speed propagating in a medium such as a liquid or the like.

Brief Description of the Drawings

Fig. 1 illustrates the configuration of an ultrasonic transducer in a first embodiment of the present invention. Fig. 1(a) is a sectional view, and Fig. 1(b) is a sectional view taken along line Z-Z of Fig. 1(a).

Fig. 2 is a planar sectional view illustrating the specific

size and shape of the electrode of the ultrasonic transducer shown in Fig. 1.

Fig. 3 is a configuration diagram of an apparatus used for observing the received waveform of the ultrasonic wave transmitted from the ultrasonic transducer having the configuration shown in Fig. 1.

Fig. 4 is an explanatory diagram in the case of applying a drive pulse of the ultrasonic transducer using the same apparatus.

Fig. 5 is a diagram showing the received waveform of the ultrasonic wave obtained when the pulse width of the drive pulse of the ultrasonic transducer is changed using the apparatus shown in Fig. 3.

Fig. 6 is a characteristic diagram showing the result of the measurement of each sound pressure of a mountain peak and a valley peak of the received waveform of the ultrasonic wave obtained when the pulse width of the drive pulse of the ultrasonic transducer is changed using the apparatus shown in Fig. 3.

Fig. 7 is an explanatory diagram illustrating a relationship between the ultrasonic wave directly emitted from the emission surface of the piezoelectric resonator and the ultrasonic wave emitted by being reflected from the open end surface of the backing layer and passing through the piezoelectric resonator 2 again in the ultrasonic transducer having the configuration shown in Fig. 1.

Fig. 8 is an explanatory diagram illustrating the comparison

between the drive pulse applied to the ultrasonic transducer and the waveform of the received ultrasonic wave.

Fig. 9 is an explanatory diagram in the case of configuring an ultrasonic transmitter/receiver by placing opposite a pair of ultrasonic transducers driven with the configuration and the condition described in a first and a second embodiments at a predetermined distance.

Fig. 10 is an explanatory diagram in the case of configuring another ultrasonic transmitter/receiver by placing opposite a pair of ultrasonic transducers driven with the configuration and the condition described in a first and a second embodiments at a predetermined distance.

Fig. 11 is an explanatory diagram in the case of setting an opposed distance in order to separate the direct wave and the diffracted wave generated with ultrasonic emission in the ultrasonic transmitter/receiver shown in Fig. 9 or Fig. 10.

Fig. 12 is a characteristic diagram showing the received waveform generated when the opposed distance between a pair of ultrasonic transducers in Fig. 11 is changed.

Fig. 13 is a graph plotting $\Delta = \{\sqrt{(R^2 + X^2)}\} - X$ using the length of the short side or the diameter 2R of the ultrasonic wave transmission surface as a parameter.

Fig. 14 is a characteristic diagram showing the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water temperature, using the ultrasonic transmitter/receiver having the configuration shown in Fig. 9.

Fig. 15 is a characteristic diagram showing the result obtained by measuring ultrasonic wave propagation time in water, which changes with a water temperature, using the ultrasonic transmitter/receiver having the configuration shown in Fig. 10.

Fig. 16 is an explanatory diagram schematically illustrating the situation in the case where there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.

Fig. 17 is a characteristic diagram showing a result obtained by measuring the propagation situation of the ultrasonic wave depending on the existence of a partition wall using the ultrasonic transmitter/receiver having the configuration shown in Fig. 9.

Fig. 18 is an explanatory diagram schematically illustrating the situation in the case where an ultrasonic wave is reflected by the existence of the partition wall when there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.

Fig. 19 is a characteristic diagram showing the result obtained by measuring the propagation situation of the ultrasonic wave with partition walls having different thicknesses when there is a partition wall between a pair of ultrasonic transducers and a substance to be measured.

Fig. 20 is a characteristic diagram showing the result obtained by measuring the propagation situation of the ultrasonic wave in accordance with the difference of the material of a partition wall using the ultrasonic transmitter/receiver having

the configuration shown in Fig. 9.

Fig. 21 is an explanatory diagram showing relationships among the density, the sound speed, and the acoustic characteristic impedance of various materials.

Fig. 22 illustrates a flow tube to be applied when the ultrasonic transmitter/receiver shown in Fig. 9 or Fig. 10 is used. Fig. 22(a) is a partially cutaway front view showing the state in which the ultrasonic transmitter/receiver is attached, Fig. 22(b) is a side view thereof, and Fig. 22(c) is a sectional view taken along line Y-Y of Fig. 22(a).

Fig. 23 is a timing chart showing relationships among a drive pulse, received ultrasonic waveforms, and measurement pulses when the sound speed in a substance is measured using the ultrasonic transducer.

Fig. 24 is a waveform chart to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in a method of driving an ultrasonic transducer of the present invention.

Fig. 25 is a waveform chart to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in the method of driving the ultrasonic transducer of the present invention.

Fig. 26 is a waveform chart to be used for an explanation for setting an optimum range of the pulse width of a drive pulse in the method of driving the ultrasonic transducer of the present invention.

Reference Numerals

1, 1a, 1b ultrasonic transducers

2, 2a, 2b piezoelectric resonators

3 piezoelectric body

31, 31a, 31b piezoelectric active portions

4, 4a, 4b electrodes

5, 5a, 5b electrodes

20, 21 ultrasonic transmitters/receivers

24 substance to be the target of sound speed measurement

25 partition wall